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ELECTRO-OPTICAL SYSTEMS, INC., Pasadena, California

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HYDROGEN-OXYGEN ELECTROLYTIC REGENERATIVE FUEL CELLS

Prepared for

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland 35, Ohio
Attn: D. G. Soltis

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Prepared by

Harvey Frank
Harvey Frank
Project Supervisor

Approved by:

E. Findl
E. Findl
Manager
Chemical and Fluid Systems

Bm. Wilmer
for A. R. Tanguay
Manager
Energy Conversion Div.

ELECTRO-OPTICAL SYSTEMS, INC.

Pasadena, California

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1. INTRODUCTION

One of the promising concepts for advancing the technology of electrochemical energy storage devices is the electrolytically regenerative fuel cell. In order to develop this concept into useable hardware for orbital and interplanetary space applications, Electro-Optical Systems, Inc., has been conducting a research and development program to define the design and operational parameters and the problem areas involved. This effort has been conducted under the sponsorship and technical direction of the Space Power Systems Office, Lewis Research Center, National Aeronautics and Space Administration (Contract NAS 3-2781).

As initially conceived, the first phase of the development program was divided into three tasks. The first task was an analytical investigation of a complete power package including a silicon solar cell power source, a hydrogen/oxygen fuel cell, power conditioner and required accessories. Both component and total system weights were calculated as a function of orbital altitude and power level. The second task involved the design and fabrication of a multicell, 75 watt device suitable for scale up to higher voltage levels. The third task consists of the testing and experimental evaluation of the cell in order to determine its operational characteristics.

This report presents the results of the test program performed under the third task during the period January 18, 1964 through June 30, 1964.

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2. SUMMARY

A six cell regenerative fuel cell was built and tested during this report period. Operational parameters and cell design features affecting cell performance were evaluated. Thirteen series of runs were conducted with varying degrees of success. In general, electrochemical performance was satisfactory. Mechanical design problems, however, eventually caused the termination of each test series. The last test series resulted in a complete failure of the fuel cell structure due to an internal combustion and fire. Results of the test program, an analysis of these results and conclusions are presented herein.

A great deal of fundamental information has been obtained from the test program. Boundary conditions and operational parameters have been determined that demonstrate the regenerative H_2/O_2 concept is feasible and practical. Therefore, a new cell will be designed incorporating features found to be desirable during this test period. Two of these new cells will be fabricated in the next quarter and the test program resumed shortly thereafter.

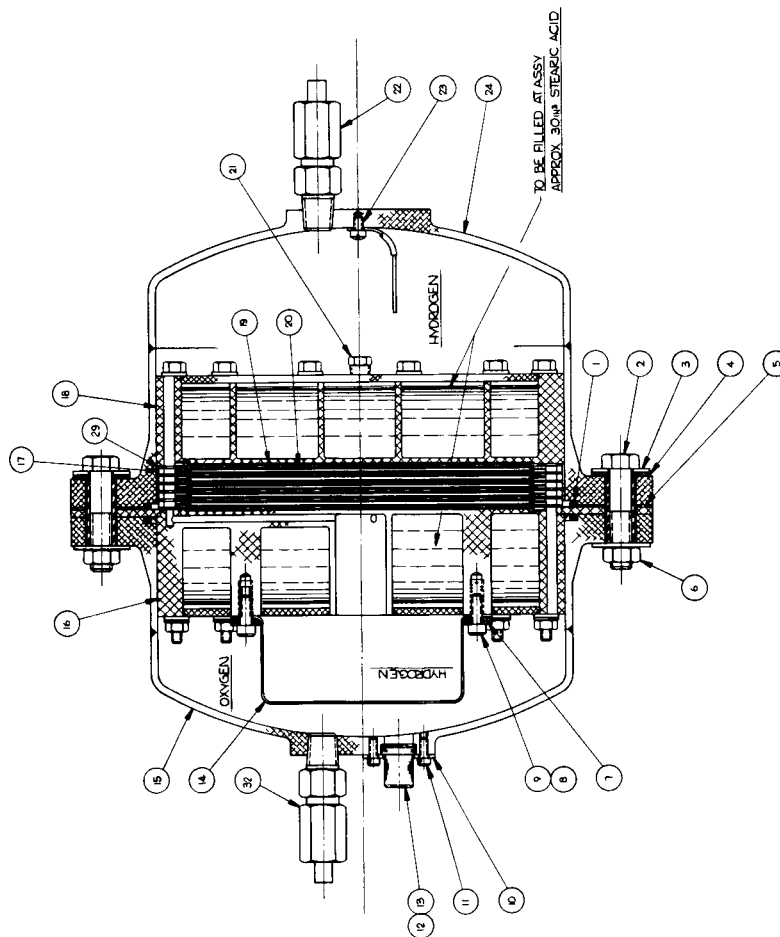
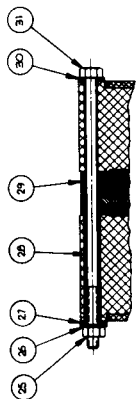
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3. TECHNICAL DISCUSSION

The major objective of the third task of the program has been to test and evaluate the fuel cell assembly. This section contains the results of all such tests performed on the unit. Before presenting these results, however, a brief review will be given of the assembly and its components.

3.1 Description of Fuel Cell

An assembly drawing of the unit is given in Figure 1 and photos of same are shown in Figures 2 and 3. The fuel cell portion of the assembly contains six series connected cells. Both hydrogen and oxygen electrodes are platinized porous nickel discs with diameter of 6 inches and thickness of .022 inches. Twenty-five percent KOH solution is employed as the electrolyte which is impregnated in sheet asbestos. Cell separators (Figure 4) are made of nickel plated magnesium and serve a three fold purpose. First, they provide recessed areas to contain the electrodes; second, they provide gas manifolds and ports to transport the gases from the gas containers to their respective electrodes, and third, they serve to connect adjacent cells in series. The end plates of the cell stack were also made of nickel plated magnesium. Bolts are passed through each of the end plates and separators to provide a means for compressing the cell stack. Gas storage containers are made of nickel plated aluminum and form an integral part of the assembly. The gas storage volume ratio is 2/1(hydrogen and oxygen respectively). Cylinder flanges contain bolt



REV	DESCRIPTION	DATE
1	INITIAL	

REV	DESCRIPTION	DATE
1	INITIAL	

REV	DESCRIPTION	DATE
1	INITIAL	

REV	DESCRIPTION	DATE
1	INITIAL	

REV	DESCRIPTION	DATE
1	INITIAL	

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REV	DESCRIPTION	DATE
1	INITIAL	

REV	DESCRIPTION	DATE
1	INITIAL	

QTY	DESCRIPTION	UNIT
1	CONAX PRES GLAND	
12	410-12267 BOLT	
12	500-005-0 PARKER STAINLESS	
6	410-12266 GASKET	
12	410-12265 SLEEVE - INSULATING	
12	410-12264 WASHER - INSULATING	
12	FLAT WASHER	
12	HEX NUT	
1	WELD ASSY - HYD TANK	
1	FLUSTER HD SCR	
1	CONAX PRES GLAND	
2	PIPE PLUG	
20	410-12262 ELECTROLYTE BED	
12	410-12263 ELECTRODE	
1	410-12261 HYD END PLATE	
5	17 410-12253 SEPARATOR	
1	16 410-12250 WELD ASSY - OXY TANK	
1	5 410-12259 WELD ASSY - OXY TANK	
1	14 4-360-21 DIAPHRAGM	
1	13 2-14 PARKER O-RING	
1	12 PRESSURE TRANS 1/2	

410-12268

QTY	DESCRIPTION	UNIT
4	11	
1	10 410-12258	
8	9 191-3 C X 1/2 HELI-COIL INSERT	
8	8	
1	1 410-12257	
12	6	
1	5 410-12256	
12	4 410-12255	
12	3	
12	2	
2	1 2-253	

QTY	DESCRIPTION	UNIT
1	10 410-12258	
8	9 191-3 C X 1/2 HELI-COIL INSERT	
8	8	
1	1 410-12257	
12	6	
1	5 410-12256	
12	4 410-12255	
12	3	
12	2	
2	1 2-253	

FIG. 1 FUEL CELL ASSEMBLY

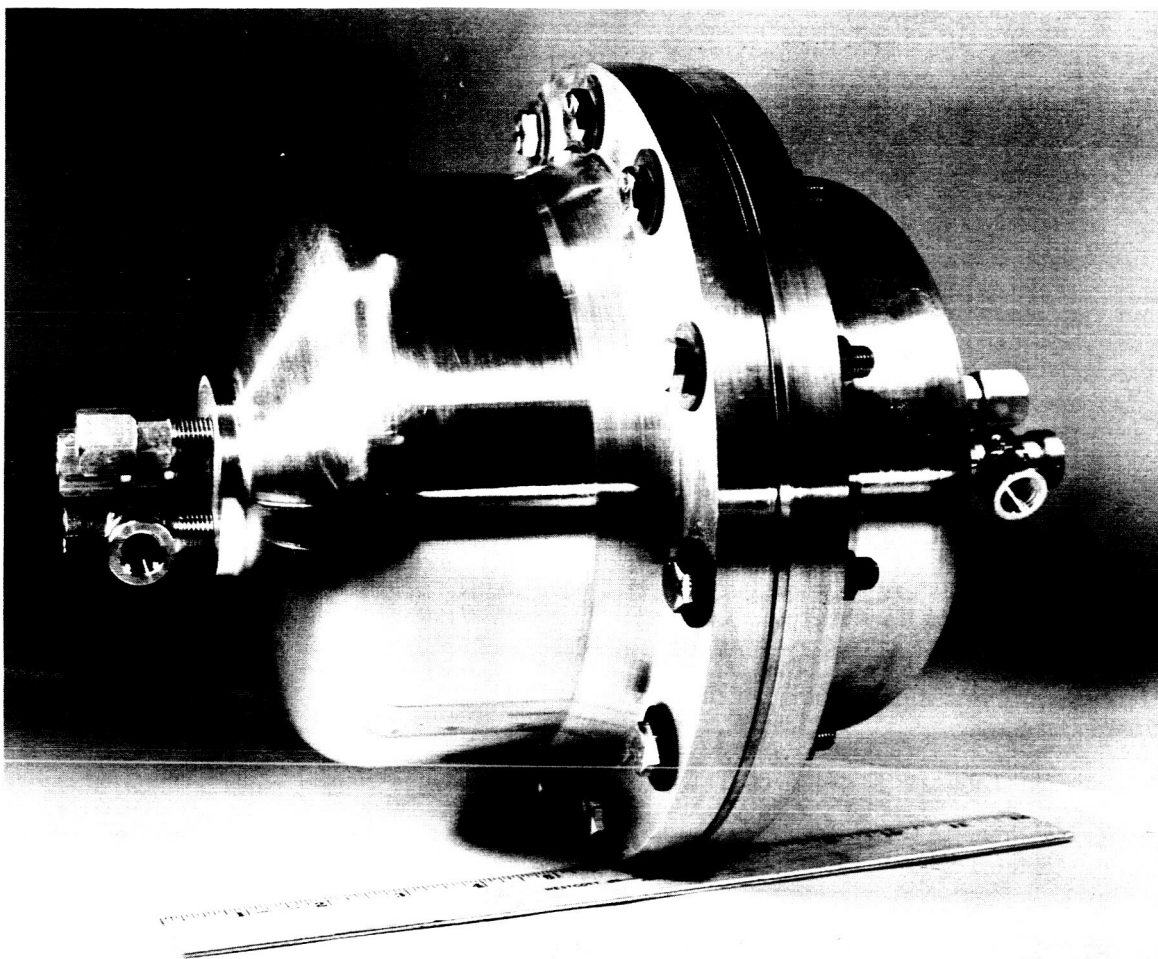


FIG. 2 FUEL CELL ASSEMBLY

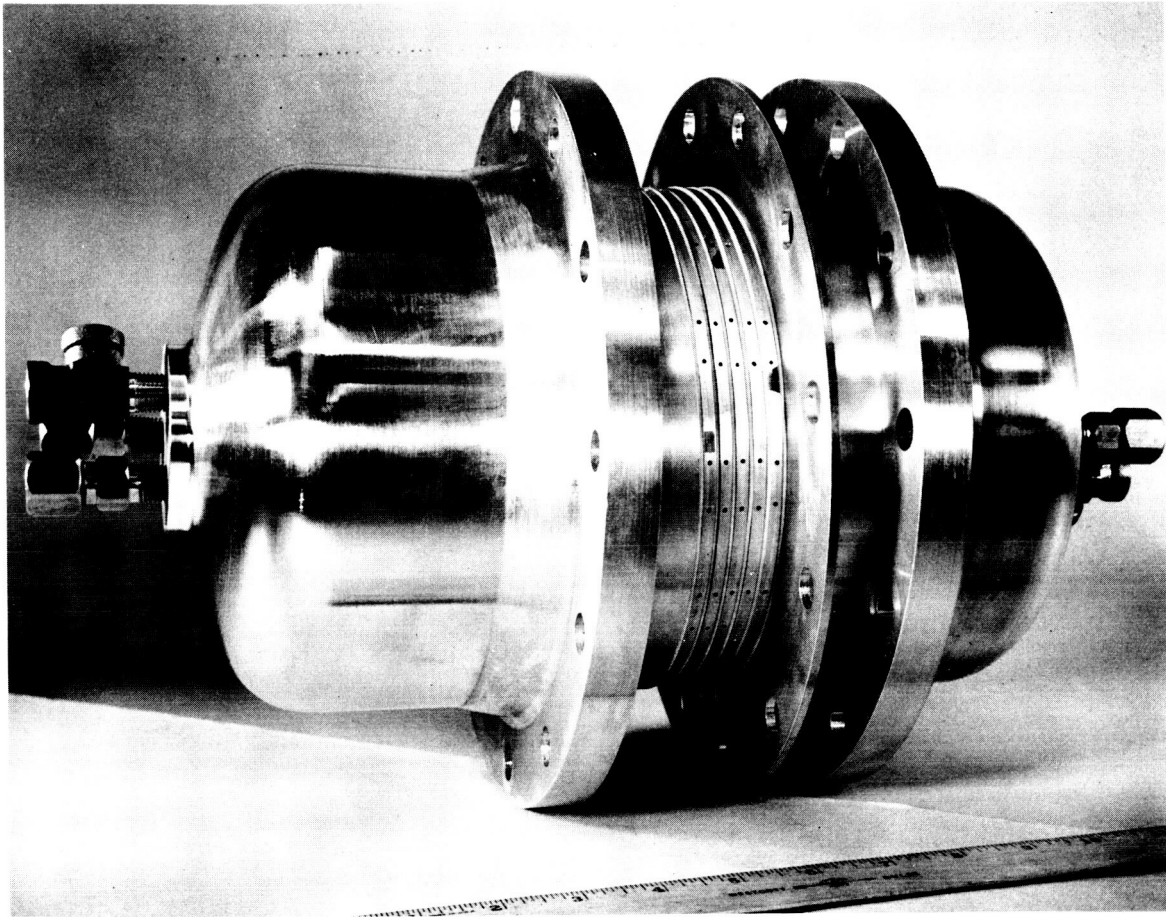


FIG. 3 FUEL CELL ASSEMBLY PARTIALLY DISASSEMBLED



FIG. 4 ELECTRODE AND SEPARATOR OF ASSEMBLY

holes to compress "O" rings located within each flange and thereby seal both halves of the assembly. Pressure balance between the hydrogen and oxygen gas chambers was accomplished by means of a rubber diaphragm. This diaphragm would either expand or shrink if a slight differential developed between the two chambers and thereby balance the pressure.

The original cell specifications called for isothermal operation. Therefore, tankage for a heat of fusion thermal storage material (stearic acid) was incorporated into the design. This tankage was made an integral part of the H₂ and O₂ end plates. During the test program, the desirability of using stearic acid was found to be questionable, and it was eliminated.

Instrumentation of the unit consisted of thermocouple leads to measure internal temperatures and voltages, a pressure transducer and a visual gauge for internal gas pressure, and finally, a differential transducer to monitor pressures between the gas chambers. Continuous cycling was carried out by means of a tandem recycle timer which switches from charge to discharge at the appropriate times. Charge current was set on the constant current power supply and discharge current was set by a rheostat. A multipoint recorder was employed to record voltage, current, temperature and pressure data during operation.

3.2 Test and Evaluation

This section presents the results and discussion of all tests performed on the fuel cell.

3.2.1 Inspection and Proof Testing

Critical dimensions of all machined parts were checked and found to be within specified tolerances. Continuity of all gas ports was checked visually and by blowing air through each port. Careful inspection of the nickel plating revealed a few pin

holes which were subsequently covered with epoxy resin. The unit was assembled with the two end plates inside the gas cylinders and hydrostatically proof tested at 500 psig. This test consisted of filling the unit with water and then applying nitrogen gas at 500 psig for 1/2 hour. The unit successfully withstood the test with no deformation of the parts.

3.2.2 Assembly and Start Up

Nickel gas distribution screens and catalyzed nickel electrodes were spot welded to the cell separators. The electrolyte bed was prepared by adding the required amount of KOH solution to the asbestos discs. Next, the cell stack was assembled, and compressed by tightening the twelve insulated bolts on its periphery. A torque wrench was employed in this phase of the assembly to obtain uniform compression. Gas ports, leading to the diaphragm pressure equalizer were blocked off for initial tests. The complete cell stack was then installed inside the gas containment cylinders. Insulated bolts on the flanges of the gas cylinders were uniformly tightened, and the unit was readied for test.

Residual air within the assembly was removed by a purging process. This process consisted of repeated pressurization of the cylinders with their respective gases, and subsequent venting to the atmosphere. Gases were admitted to and released from the cylinders simultaneously, and slowly, using needle valves. A differential pressure gage, connected across the cell, was employed to keep the differential pressures to a value less than 1.0 psi during the purging operation. After completion of this operation, the unit was ready for electrical testing.

3.2.3 Cycle Tests

This section presents the results and discussion of all cycle tests conducted on the unit. A brief summary of each of the tests is given in Table 1 and a more complete description is given below.

3.2.3.1 Run No. 1

The object of the first cycle test was to evaluate the functionality of the fuel cell as installed within the assembly. For this purpose, the unit was run in a "quasi-secondary" mode of operation described in the 2nd quarterly report. As a preliminary check out, the unit was assembled with just one cell using one layer of nominal 0.070 inch thick commercial asbestos as the separator. The initial voltage-current and cell impedance measurements indicated a relatively high internal cell resistance of 0.035 ohms at 25°C. Improved electrical contacts were installed and the single cell resistance was reduced to the acceptably low value of 0.008 ohms at 25°C. At 67°C this becomes 0.003 ohms.

Subsequent tests were carried out with six cells, using the 0.070" asbestos. The impedance of the complete assembly was 0.048 ohms at 25°C. The initial charge-discharge characteristics for the 6-cell unit are given below. The charge cycle was performed at design current and duration, i.e., 9.6 amps for 76 minutes. However, due to the low operating temperature and reduced gas pressure, the discharge cycle was performed at below rated current for an extended duration to simulate the rated amp-hours.

* 4110-QL-2, 18 January, 1964, Pg. 11.

TABLE 1
SUMMARY OF CYCLE TESTS

Run No.	Date	No. Cycles	Temp. °C	Press (psig.)	Charge		Discharge		Purpose and Comments
					Volts	Amps	Volts	Amps	
1	2/13	4	28-64	0 Ch 100 Dis. 150 Dis.	10-12	9.6-10	3.0-4.8	10-15	Check out test while operating in "quasi-secondary" mode of operation. Ignition occurred while adjusting pressures.
2	2/18	3	28-42	52-200	10.4-12.2	10	3.2-4.8	8-10	First run in actual secondary operation. Low power output indicated contaminated electrodes.
3	2/27	1	30	-	9.5-12.5	9.6	-	-	First run with complete instrumentation. Ignition occurred at beginning of discharge.
4	3/1	1	35-40	-	9-18.7	2-8	4.5	10	Test with new viton bellows and new set of electrodes. Ignition occurred on discharge. Found internal crack in O2 end plate.
5	3/25	6	30-60	50-200	9.6-11	9.6	2.7-5.0	10-30	Test with new electrolyte layer and differential pressure transducer. Found build up in excess H2 pressures. Ignition occurred at beginning of 6th discharge.
6	4/7	7	27-50	40-240	-	-	-	-	Adjusted gas volumes for each cycle until proper volume ratio was obtained.
7	4/9	5	29-57	55-320	9.8-10.2	9.6	3.9-4.5	15.8-16.7	Began final continuous cycle test. Ignition occurred in middle of 5th discharge period.

TABLE 1 (con.)

Run No.	Date	No. Cycles	Temp. °C	Press (psig.)	Charge Volts	Charge Amps.	Discharge Volts	Discharge Amps.	Purpose and Comments
8	4/29	6	31-60	50-302	8.9-10.1	9.6	3.5-4.8	16-18	Began another continuous cycle test. Internal short circuit developed during 5th discharge period. Turned off.
9	5/5	1	28-46	50-287	9.8-10.5	9.6	4.3-4.5	17.7-18.2	Began another continuous cycle test. Ignition occurred during first discharge period.
10	5/15	19	28-70	50-380	9-10	10	3.6-4.5	16-19	Longest cycle test of 36 hrs. Performance dropped near end.
11	5/25	5	30-63	50-270	10-13	10	3-4	10-11	Cycle test with new set of electrodes and gaskets and electrolyte. Low performance throughout.
12	5/27	1	28-37	50-265	10.0-10.6	9.6	3.4	5	Check out test. Found two reversed cells.
13	6/8	4	62-83	54-315	9.0-9.3	8	5.0-5.1	12-13	Replaced electrodes of reversed cells and began cycle test. Started cycle test at higher temp. Good performance until sudden combustion.

Charge at 9.6 amps with internal temperature near 50°C and 1 atm gas pressure.

Time (min.)	Volts
0	8.8
20	9.8
40	9.9
60	10.0
76	10.1

Discharge at 8 amps with internal temperature near 50°C and 100 psig gas pressures:

0	4.8
25	4.9
50	4.9
75	4.9
91	4.9

For subsequent cycles it was deemed advisable to begin testing at or near rated conditions in order to establish whether or not the unit would meet the design goals. In the next cycle it was therefore decided to increase temperature to 60°C and pressure to 150 psig. The unit was placed on various loads (to 30 amps) at these conditions, and it appeared to be functioning properly. During the course of adjusting the gas pressures to a higher level, a sudden noise was heard within the unit, and the hydrogen gas pressure was noted to increase rapidly to 10 psi above the oxygen pressure. The unit was subsequently turned off, and the gases vented from their chambers.

Disassembly and examination of the unit revealed signs of a minor combustion within the gas chambers, i.e., the metal surfaces were slightly tarnished, and a small amount of electrolyte had been expelled from the cell stack. Since there was no apparent damage, the stack was not disassembled.

It was believed at the time that the cause for the above malfunction was associated with the mode of operation of the unit, i.e., the quasi-secondary mode of operation. In this process

the gases are supplied manually from externally located cylinders during discharge. Specifically, it was believed that improper manual control of the gas pressures caused mixing of the two gases, and resulted in a thermochemical reaction, the ignition being supplied by either an internal arc or by contact of the gas mixture with the platinum catalyst. (Later results showed that the gas mixing was due to the type of asbestos separator employed in this assembly.)

The next cycle was carried out in the same mode of operation, but with the addition of the rubber diaphragm to the assembly. It was believed that the use of the diaphragm would permit better control of gas pressures and thereby prevent mixing. Another reason for installing the diaphragm at this point was that if the next test series proved successful, the unit could merely be sealed off from the external gas cylinders and run in the true secondary mode of operation. (The diaphragm is an integral part of the assembly for this mode of operation).

Subsequent cycle testing indicated little improvement in performance over the previous test. The maximum current for relatively stable voltage within the desired range of 3.5 to 4.5 volts through the discharge period was found to be in the range of 10 to 15 amperes. Three such cycles were carried out over a range of temperatures from 25^o to 65^oC and gas pressures from 100 to 150 psig.

3.2.3.2 Run No. 2

It was decided to seal off the gas cylinders and continue testing in the true secondary, i.e., the regenerative mode of operation. Gas pressures of 50 psig were applied to the cylinders at the start of the first cycle. The unit was charged at a constant current of 10.0 amps for 15 minutes. Gas pressure increased linearly with time during the charge to 100 psig, and the terminal voltage increased gradually from 9.0 volts to 11.9 volts. The initial internal temperature was 28^oC and the final was 29^oC. The unit was then discharged across a fixed load. The initial discharge characteristics were 4.5 volts at a current of 10 amps. The performance gradually

declined during the course of the discharge to the initial pressure of 50 psig at which the voltage was 3.5 volts at a current of 5.8 amps. Internal temperature increased from 29 to 32.5°C during the discharge. The unit was then charged at 10 amps for a longer period, i.e., 44 minutes. Final gas pressure was 200 psig, the voltage 12.2 volts, and the temperature 34.5°C. Initial discharge characteristics after 200 psig level were found to be slightly higher than on the previous short cycle (due most likely to the elevated pressures). However, performance gradually declined as before during the course of the discharge period.

Although the discharge performance was slightly higher at the elevated pressure, the improvement was not sufficient to meet the design goals, i.e., 75 watts. In addition, the charge voltage per cell was somewhat higher than that which had been observed in single cell tests. These observations pointed to the possibility that the electrodes had been contaminated during the course of handling and testing. The decision was therefore made to disassemble the cell stack and clean each of the electrodes. The cleaning was carried out by passing boiling distilled water over each until the filtrate had a pH of 7, using phenolphthalein as the indicator. The old electrolyte discs (KOH + asbestos) were discarded, and a new set was prepared for the next tests. Thermocouple and voltage probes were also installed in the unit for the following tests.

3.2.3.3 Run No. 3

Cycle testing was subsequently continued with the measurement of individual cell voltages and temperatures. During the first charge period, large differences in cell voltages were found, ranging from 1.70 to 2.20 volts at a current of 9.6 amps. This result indicated non-uniform electrodes. At the beginning of the first discharge period there were a few internal noises heard similar to Run. No. 1. In this case, the noises were louder, and the internal temperature increased rapidly from 30°C to 60°C. The unit was turned off, and the gases were vented.

Disassembly and inspection revealed that the bellows had been completely burned, and that the carbonaceous deposits from same were spread throughout the tanks and cells. In addition, it was found that the thermocouple wires adjacent to the bellows had been burned. The initial explanation for this malfunction was that expansion of the bellows caused a shorting of two thermocouple wires (which are attached to adjacent cells) resulting in ignition and burning of the bellows. (In the light of later results, however, it is believed that the thermochemical reaction was simply due to bulk-gas mixing due to the high porosity of the 0.070" asbestos and subsequent ignition at the electrodes.)

At this point the unit was completely disassembled, and the electrodes, as well as electrolyte discs were discarded. Each of the cell separators was thoroughly cleaned, and new electrodes were inserted and spot welded onto their respective sides of the separators. New thermocouples were installed and extra care was taken in insulating and positioning each couple so as to clear the bellows. A new bellows made of viton rubber was used as a replacement for the previous one which had been made of butyl rubber.

The choice of the material of construction for the diaphragm is subject to discussion. Use of butyl rubber was based upon its property of having very low gas permeability. The possibility of oxidation of the butyl was not overlooked, and an oxidation test was carried out on a sample of the material as described in a previous report. Results of this test indicated a very small amount of oxidation of the rubber had taken place over the course of one week. Since the test conditions were more severe than would be found in actual cell operation, it was deemed suitable for at least the preliminary test period. The viton diaphragm was not immediately employed because of a slightly different configuration, which necessitated modification of one of the end plates.

3.2.3.4 Run No. 4

The unit was again reassembled, and another cycle test was initiated. Initial results of the test appeared very encouraging. Charge voltages of each cell were much more uniform and lower than on previous runs, i.e., 1.72 to 1.77 volts at 8.0 amps at room temperature. The initial discharge characteristics also appeared to be very good at the start of the discharge period, i.e., the initial voltage and current values were increasing rapidly as the internal temperature was increased. Suddenly, however, another thermochemical reaction occurred within the assembly. The dial of the 600 psig pressure gage mounted on the cell indicated > 600 psig. In spite of this large pressure increase, there was no apparent damage to the gas containers or flanges. The load was removed from the cell and the residual gases vented to the atmosphere.

Subsequent testing of the cell stack with nitrogen revealed that it could not hold a pressure differential across the two gas cylinders, i.e., gases flowed readily across the cell stack upon application of only a fraction of a psi differential. Disassembly and examination of the unit revealed a crack in the welded flange of the oxygen end plate. The oxygen end plate was repaired and a review of the program was carried out at this time as described in the next section.

3.2.3.5 Interim Review

A critical review of the program was carried out at the end of the above cycle. The results of this review indicated the source of all of the previous malfunctions were associated with intermixing of the two gases. This mixing leads to ignition via the electrode catalysts. There appeared to be three possible reasons for this mixing, i.e., (a) the teflon gaskets did

not seal between the gas ports (b) the asbestos matrix did not seal at its periphery and (c) the permeation/diffusion rate through the asbestos matrix was higher than anticipated.

3.2.3.6 Modifications and Leak Testing

Before proceeding with any additional performance testing, it was necessary to locate the source of the internal gas leaks. When the oxygen end plate had been repaired, a series of leak tests were carried out on the assembly. The tests consisted of applying a small differential pressure (1/2 psi) to one side of the assembly and then checking for leaks out of the gas manifold with a special detergent.

The first item to be examined was the gaskets. An initial attempt was made to employ viton instead of teflon gaskets. This approach was discarded, however, when it was found that there was excessive extrusion of the viton gaskets upon compression of the stack. Next, it was decided to coat the surfaces of the teflon gaskets with an additional sealant. An uncured viton compound was employed for this purpose. Leak testing revealed no reduction in the internal leak rate. Subsequently, it was decided to employ a new set of teflon gaskets. Leak testing again revealed no reduction in the internal leak rate. These first two tests then tended to indicate that the source of the internal leaks was not associated with the gaskets.

A subsequent leak test was carried out with only one cell inside the assembly. The compression on this cell was increased for this test by increasing the torque on the twelve bolts from 50 to 90 inch pounds. Again there was found to be no reduction in the leak rate. Disassembly and examination of the cell indicated that the asbestos matrix had been properly centered, and that its outer periphery (sealing surface) had been seated very well against the two end plates. This result then tended to indicate that the source of the internal leakage was not associated with the sealing of the asbestos matrix.

In the next test it was decided to evaluate another type of asbestos matrix. This other type of asbestos had been employed with good results on a previous fuel cell program (NAS 7-100). Since the thickness of this material (0.035") was half that of the type which had been employed previously, two layers were employed in the cell. Subsequent leak testing revealed a complete stoppage of the internal leaks. No leaks were found at differential pressures to 5 psi.

This latter result indicated that the internal leakage was due to diffusion of the gases through the asbestos matrix. It was therefore decided to employ two layers to this thinner asbestos in each cell for subsequent tests.

3.2.3.7 Run No. 5

The objective of this run was two-fold. First, it was desired to evaluate performance with two layers of the 0.035" asbestos matrix as described in Section 3.3.3.6. Second, it was desired to obtain further information on internal cell operation using a differential pressure transducer.

The fuel cell stack was completely reassembled for the next test. A new set of electrodes and two layers of 0.035" asbestos were used. The differential pressure transducer was connected externally to both hydrogen and oxygen containers.

The unit was cycled several times at approximately 1/3 of the designed depth of discharge. During the course of these cycles a linear increase in hydrogen differential pressure was noted with state of charge. This result signified that the volume occupied by the hydrogen was less than the design requirements, i.e., less than two times the volume occupied by the oxygen.

At the beginning of the discharge portion of the sixth cycle, the unit was shut down and disassembled due to another internal ignition.

Attention was now focused on the possibility of pressure imbalance being a major contributing factor to internal ignition. If a large discrepancy exists in the required 2/1 volume ratio, a high pressure differential could be developed causing the gases to mix via flow through the asbestos matrix. The mixed gases could then be ignited by the catalysts. Differential pressure readings in the above run indicated excess hydrogen pressure to the extent of nearly 1 psig at a relatively low state of charge. At higher states of charge, the hydrogen differential could be increased to such an extent that flow across the asbestos matrix could readily occur.

A check was subsequently made on the original design volume calculation and the existing volumes. A discrepancy was found between the two, and was associated with a design change in the bellows, neglect of volume inside the gas ports, and small dimensional variations.

3.2.3.8 Run No. 6

The object of this run was to test functionality after having adjusted the gas volumes to the proper ratio. For this purpose a small steel cylinder (8 in.³ volume) was attached to an external fitting of the hydrogen tank and the unit cycled with measurement of differential pressure. The additional volume was found to be insufficient as indicated by a positive H₂ differential pressure. Various sized tanks were then added until the proper volume ratio was obtained, as determined by essentially no change in differential pressure throughout the cycle.

3.2.3.9 Run No. 7

After having adjusted the gas volumes, it was decided to begin the 48 hour continuous cycle test. The unit was carried through two short cycles and found to function very well. It was then carried through a complete charge-discharge cycle at the required currents and cycle times. Since the results of this test also indicated favorable performance, the unit was

placed on automatic cycling to begin the 48 hour test.

Performance of the unit during the first five cycles is given in Figures 5 and 6. Electrical performance (Fig. 5) indicates a relatively constant charge voltage near 9.6 volts during charge at 9.6 amps and a relatively constant discharge voltage at 4.5 volts at a current of 16.6 amps. The above performance met the design goals of the contract in regard to voltage and power output. Internal temperature, (Fig. 6) (measured on the hydrogen end plate) indicated a temperature rise during discharge and a fall during charge. This result can be explained by the thermodynamics of the hydrogen-oxygen reaction. During discharge, the unit generates heat from internal polarization losses as well as from the entropy change " $T\Delta S$ " of the reaction for the formation of water. During charge the unit generates a much smaller amount of heat from polarization losses and absorbs heat from the entropy change accompanying the decomposition of water. The "steady state" temperature range appeared to be 58°C at the end of discharge and 54°C at the end of charge.

Small fluctuations of the gas pressures were noted throughout the third, fourth and fifth charge and discharge periods. The magnitude of the fluctuations were approximately ± 0.05 psi. The frequency of the fluctuations was rather erratic. Individual pulses occurred at one to two minute intervals sometimes accompanied by a rapid series of pulses. A few instantaneous fluctuations of > 0.05 psi excess hydrogen pressure were also noted. No significance could be attributed to these fluctuations at the time, save perhaps some minute local ignitions of gas mixtures on the electrodes. Later tests showed this fluctuation to be due to instrumentation noise.

At the end of the fifth cycle another malfunction occurred within the unit. A slight noise was heard, the gas pressures and temperature rose suddenly, and the discharge voltage and current slowly dropped to zero. Disassembly and examination of the unit revealed signs of another internal ignition. (See Fig. 7)

T= 51° TO 57°C
P= 75 PSIG AT START OF CHARGE
320 PSIG AT END OF CHARGE
ELECTRODE AREA = 28.3 IN.²
NO. CELLS = 6

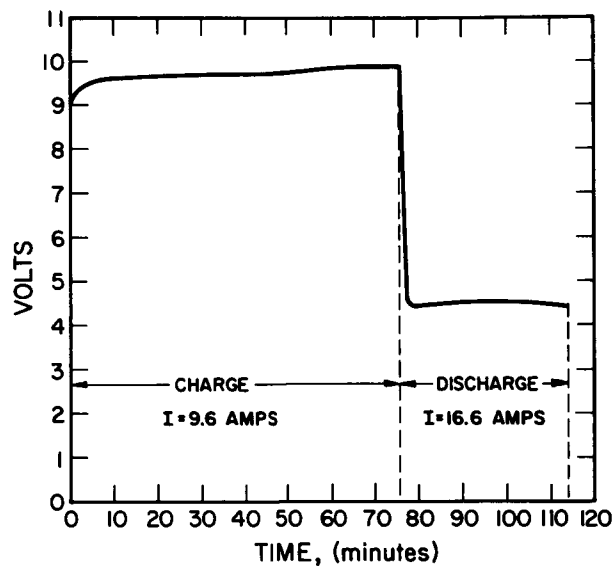


FIG. 5
ELECTRICAL PERFORMANCE
IN RUN NO. 7

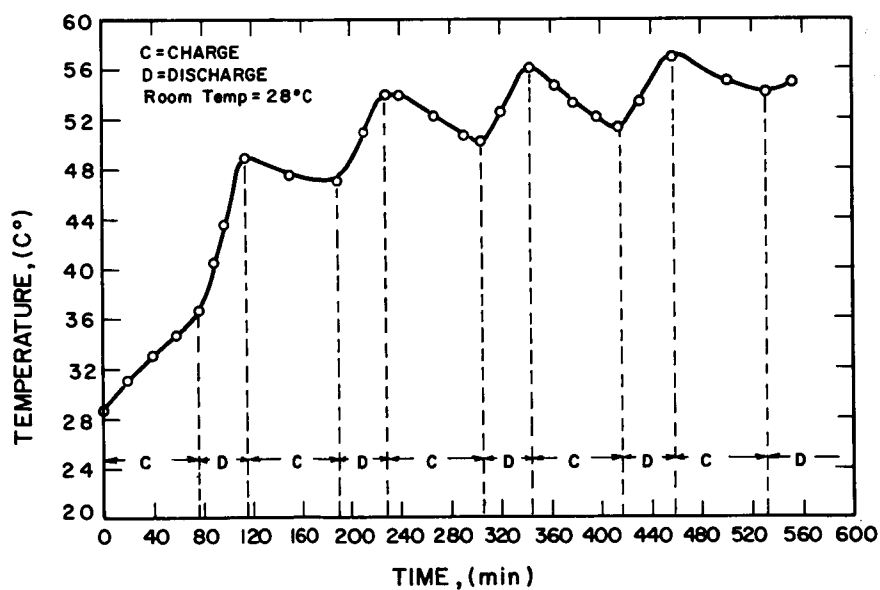


FIG. 6
INTERNAL TEMPERATURE
IN RUN NO. 7

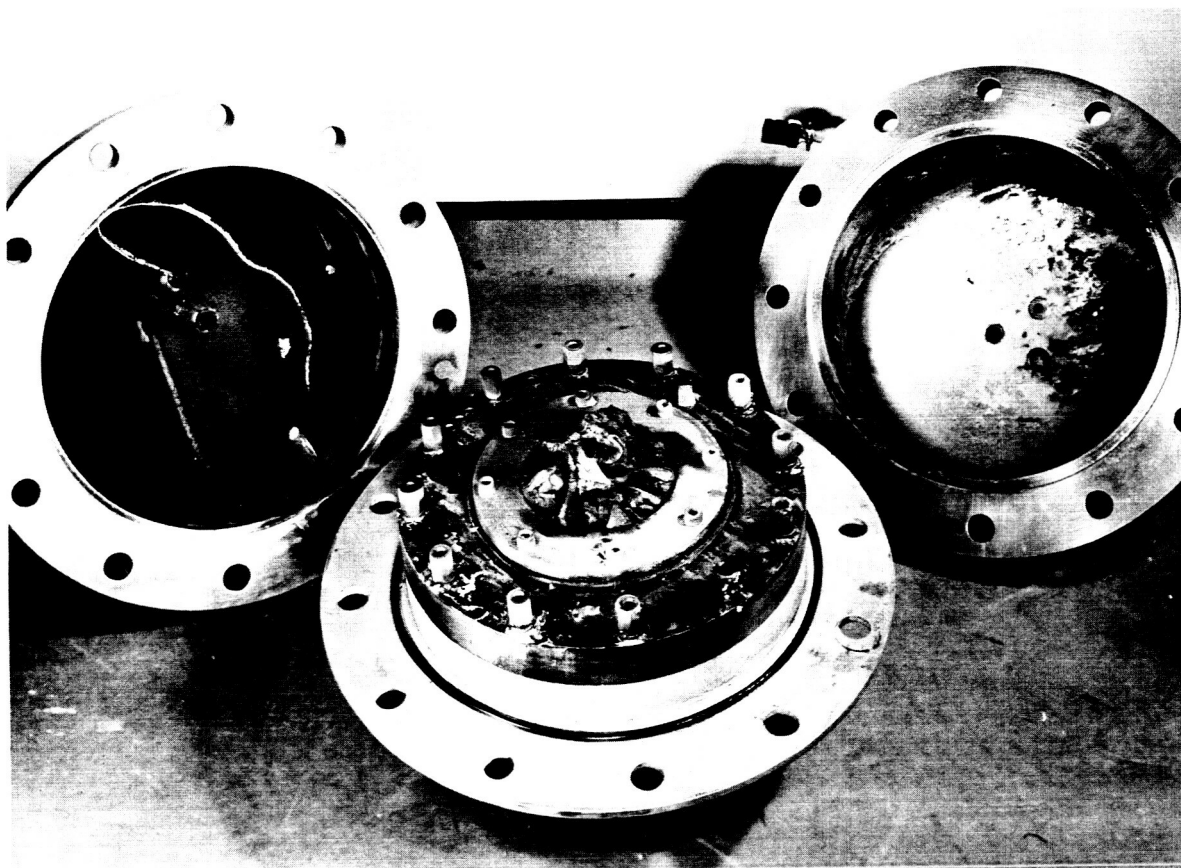


FIG. 7 FUEL CELL AFTER TYPICAL INTERNAL IGNITION

The pressure fluctuations were then assumed to be indications of cell instabilities and as precursors to ignition. However, this was shown to be incorrect in later runs.

3.2.3.10 Run No. 8

Several additional modifications of the fuel cell were subsequently carried out in order to eliminate possible sources of the internal ignition. First, it was decided to employ a fabric reinforced rubber bellows for added strength in this critical area. An order was subsequently placed with a local vendor to fabricate a nylon reinforced viton rubber bellows. The vendor reported difficulty in fabricating with viton and suggested silicone rubber as an alternative. A nylon reinforced silicone rubber bellows was subsequently obtained and installed on the assembly.

A second change consisted of installing a new set of hydrogen electrodes which contained only platinum as the catalyst. Previously these electrodes contained a mixture of both platinum and palladium catalysts. The reason for this change was based on the high reactivity of palladium in regard to ignition of hydrogen-oxygen mixtures. It was reasoned that there would be less likelihood of another ignition without palladium, should gas mixing occur within the assembly.

A third and final change consisted of adding more electrolyte to the asbestos matrices before assembly. The change corresponded to an increase in the amount of electrolyte from 0.6 to 0.7 gms. of 25% KOH solution per gram of dry asbestos. The purpose of this change was to insure the presence of sufficient water within the matrices at full state of charge, thereby limiting the rate of gas mixing through the matrices. When all of these modifications had been completed, the unit was readied for cycle testing. The unit was found to function very well for five cycles. The power output during each of the discharge periods was in excess of the required 75 watts, and the charge voltage was less than 10 volts for each charge period. During the discharge portion of the 6th cycle, however, an abnormal drop in voltage, a rapid pressure drop and rise in internal temperature

was noted. During the subsequent charge period, an abnormally low charge voltage was also noted. These results all pointed to the probability of an internal short circuit of one of the cells. The unit was subsequently turned off and disassembled. Inspection of the cell stack confirmed the presence of a shorted cell, first by probing with an ohmeter, and second by visual examination. The cause for the internal short was found to be associated with one of the teflon gaskets. This gasket had been employed on previous runs, and had been deformed by cold flow to a thickness of ≈ 0.030 ". (Normal gasket thickness is 0.043 ").

3.2.3.11 Run No. 9

A new set of teflon gaskets was subsequently obtained from a local vendor. Inspection of this new set revealed small dimensional deviations from the required specifications. There was therefore some concern as to whether to continue testing with this new set of gaskets. The gaskets were reworked, and it was decided to attempt another test run.

In the next test, an internal ignition occurred during the latter portion of the discharge period of the first cycle. Disassembly and examination of the cell stack revealed the source of the ignition to be associated with one of the new teflon gaskets. The gasket had been extruded to such an extent in the initial assembly that there was a direct opening between a hydrogen gas port and an oxygen electrode. This latter result reaffirmed the need for maintaining very rigid quality control over all materials used in the assembly. After a careful review, it was decided to change the gasket material from teflon to viton. It was anticipated that this change would avoid the cold flow and resultant problems associated with the teflon.

3.2.3.12 Run No. 10

As a result of the teflon gasket failures described above, a new series of tests was initiated to evaluate performance with rubber gaskets and different grades of asbestos. In addition, an assembly check list procedure was initiated to insure closer quality control and to maintain a record of the individual steps taken during the assembly and checkout of the cell stack.

One of the steps taken during the assembly of the cell (taken as a result of asbestos leakage problems noted previously) is to pressurize the cell stack to 1/2 psig with one tank half left off. Leakage, if any, through the cell stack can then readily be determined by the use of a detergent solution. The cell stack was found to have a small leak, about one bubble per minute. This rate, although small was deemed to be unsatisfactory. Subsequent investigation showed that the leakage was not through the stack, but due to pin hole leaks in the periphery of certain separator plates. These leaks were in the epoxy plugs in the peripheral drill holes used to feed the gases from the gas manifolds to the electrodes. It is believed that these leaks were a major factor in the failures of runs 5 and 7.

This test was made using viton rubber gaskets. Unfortunately, the gaskets used were about 0.010 inch thicker than desired, i.e., 0.053 inch. This required a modification of the asbestos matrix separator bed in order to maintain an approximate 7/4 compression ratio on the asbestos. The modification consisted of the addition of a third layer of asbestos, 0.020 inch nominal thickness, between the standard two layers of 0.035 inch nominal material. Other modifications made on this run were as follows:

1. Electrolyte/asbestos weight ratio increased to 0.73 from 0.70.

2. Cell evacuated to \approx 20 inches Hg (gauge) prior to purge.
3. Cell charged for a few minutes at ambient pressure prior to starting run.

Results of Run No. 10 (See Fig. 8) were quite encouraging in that the cell ran for about 36 hours prior to an apparent cell degradation problem. Cell performance was not, however, typical of that achieved during prior testing. Initially, this was attributed to electrode flooding caused by the higher electrolyte to asbestos ratio used. However, subsequent drying of the electrode/asbestos matrix by electrolysis did not significantly improve performance. Analysis of permeability data, plus data from the following run, indicate that the 0.020 inch type asbestos material used causes concentration polarization, due to an apparent decrease in porosity and subsequent decrease in the availability of OH^- ions.

Near the end of the 36 hour period, cell performance began to deteriorate rapidly on discharge. A rapid decline in cell voltage indicated that a cell reversal had occurred. Inasmuch as such a cell reversal could result in bulk gas mixing plus drying out of the asbestos of the reversed cell, it was decided to terminate this run. No apparent cause for the cell reversal was determined upon disassembly of the cell.

There are but three pertinent causes for cell reversal in the regenerative H_2/O_2 cell. These are poor electrodes, electrolyte contamination and gas port blockage. Each of these factors was evaluated. No gas port blockage could be determined. The electrolyte was reanalyzed and found to be well within tolerance. This left electrode contamination as the most likely cause of reversal. Therefore, a new set of electrodes was prepared.

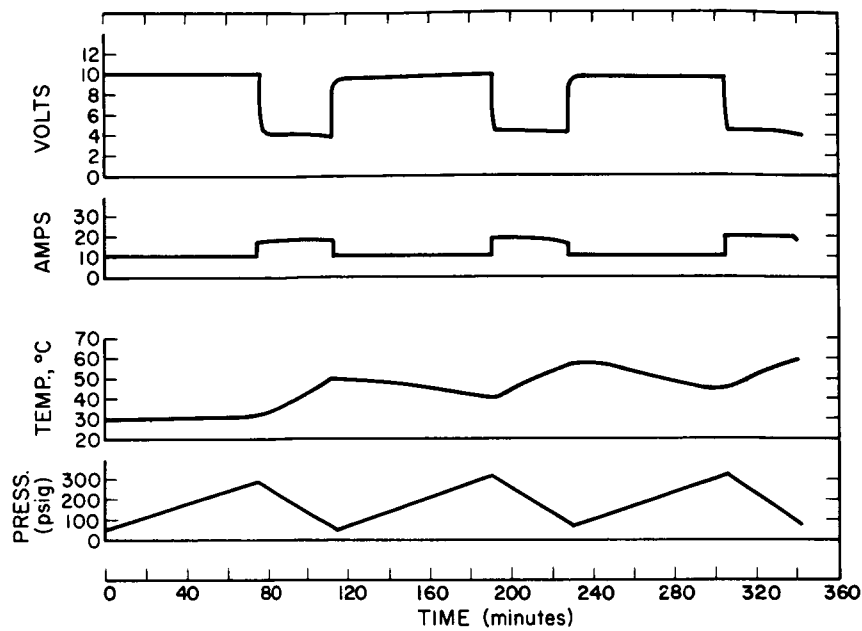


FIG. 8
PERFORMANCE OF UNIT
IN RUN NO. 10

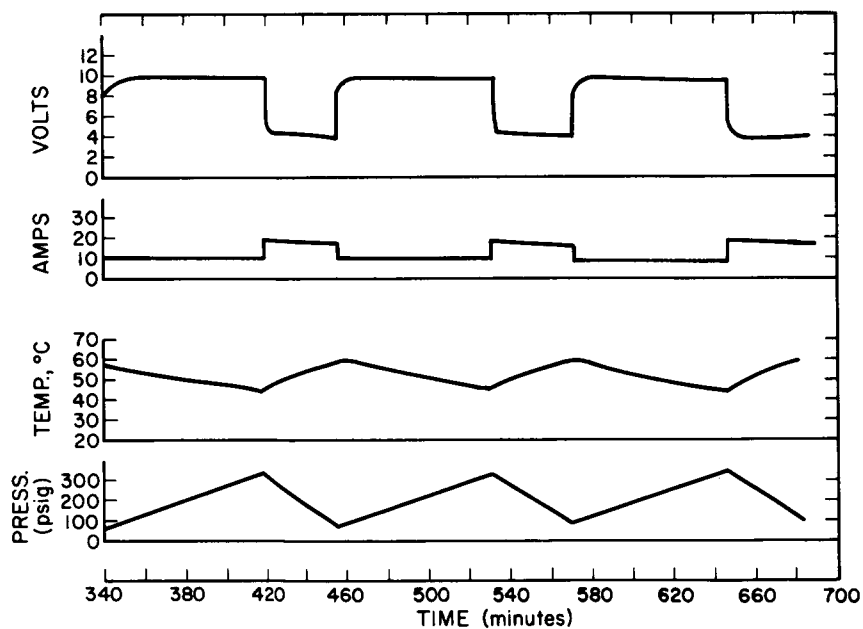


FIG. 9
PERFORMANCE OF UNIT
IN RUN NO. 10

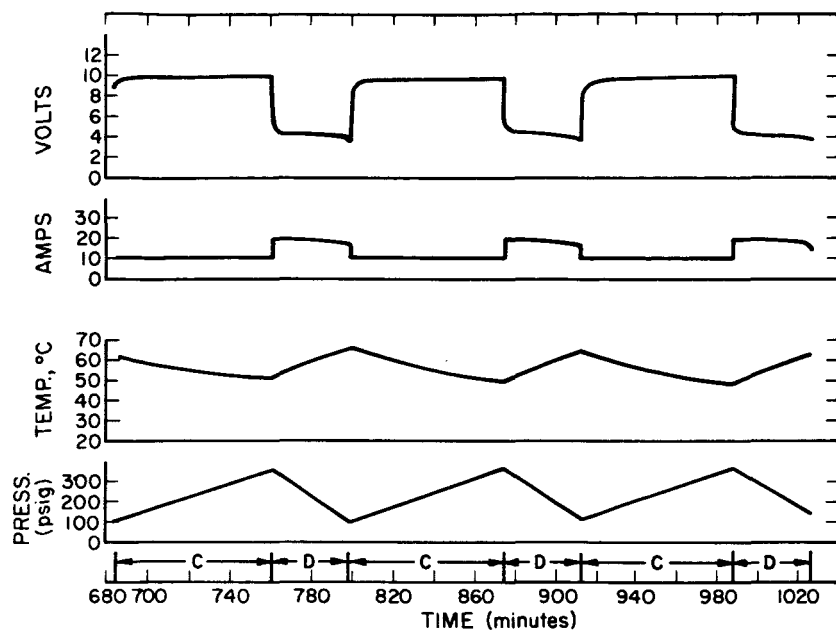


FIG. 10
PERFORMANCE OF UNIT
IN RUN NO. 10

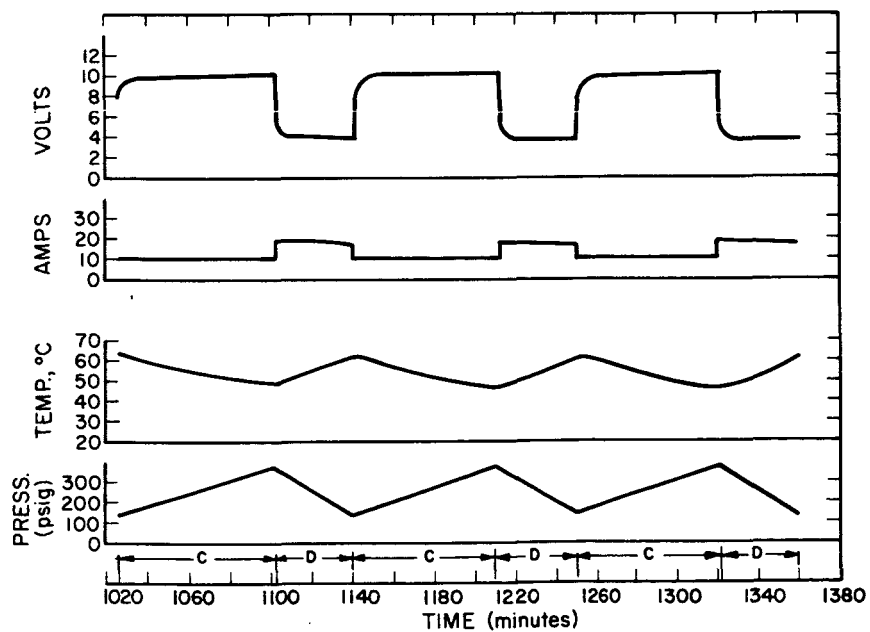


FIG. 11
PERFORMANCE OF UNIT
IN RUN NO. 10

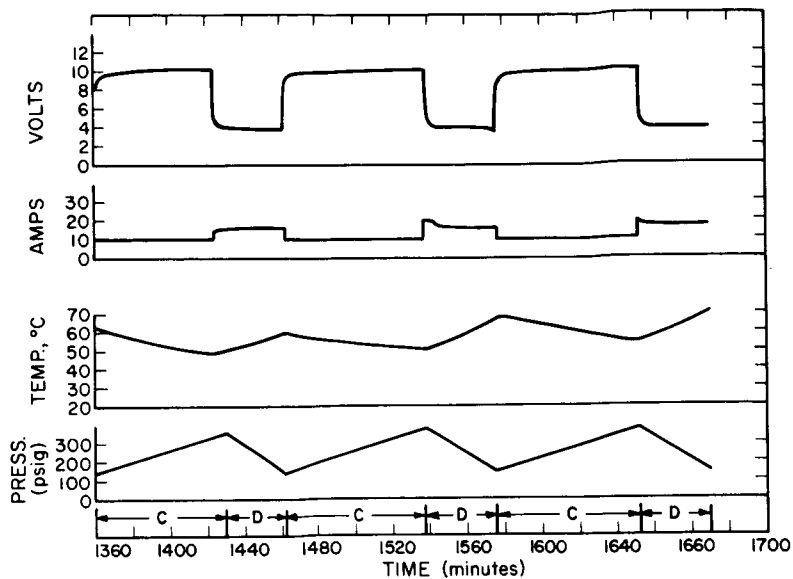


FIG. 12

PERFORMANCE OF UNIT
IN RUN NO. 10

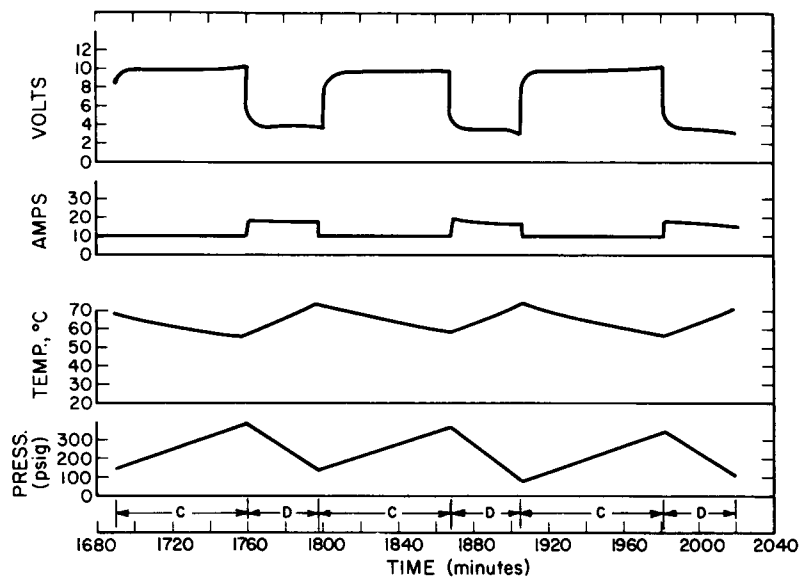


FIG. 13

PERFORMANCE OF UNIT
IN RUN NO. 10

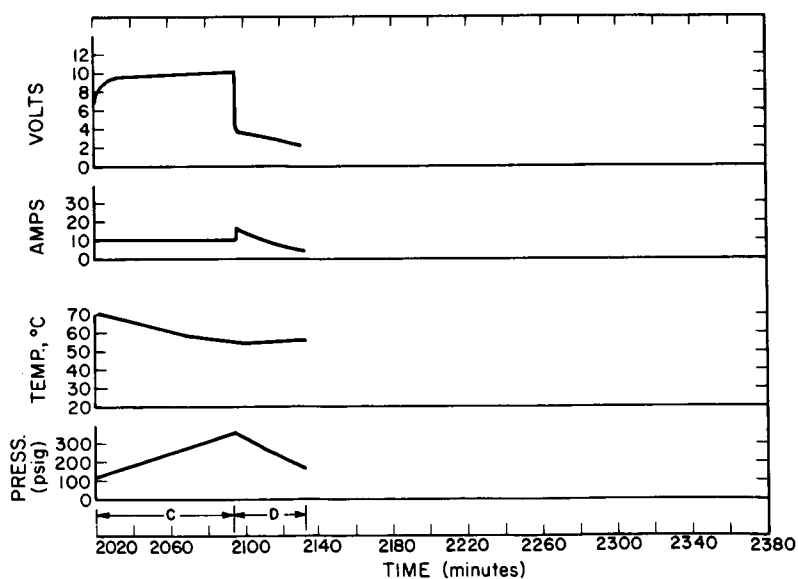


FIG. 14

PERFORMANCE OF UNIT
IN RUN NO. 10

3.2.3.13 Run No. 11

This run was made using a new set of electrodes. Due to the problem in obtaining suitable viton gaskets, it was decided to use silicone rubber gaskets. Here again, the inability of the gasket material supplier to hold the desired tolerance caused a change in assembly procedure. This time, the gaskets were about 0.048 inches thick, again causing a modification in the asbestos matrix used. In order to maintain an approximate 7/4 compression ratio, two layers of 0.020" material and one of the 0.035" material were used.

During the initial cycle, an unusual variation of the pressure differential in the cell was noted. It appeared that the pressure differential was a function of the charge or discharge rate rather than a function of time. This is indicative of an internal leak into the supposedly sealed thermal storage (stearic acid) container compartments. After 1 cycle, the cell tanks were disassembled and the leakage confirmed. The plug sealing the stearic acid chamber was removed, and the cell reassembled. (Note--stearic acid had been removed from all compartments prior to Run 10). This process eliminated the pressure variation and the run was continued.

Cell performance was poor during this run on both charge and discharge. By introducing gases from external sources and discharging the cell, thus in effect adding water, the cell performance during charge could be improved slightly. This indicated that electrolyte migration from the asbestos to the electrodes was being impeded. After about 10 hours of operation with little significant improvement, the run was terminated.

3.2.3.14 Run No. 12

Run 12 was initiated using silicone gaskets from the same batch as Run 11. Instead of using the 0.020 inch material, however, two layers of 0.035 material were used. At the standard cell stack torque of 40 inch pounds, however, these materials did not give a 7/4 compression ratio on the asbestos because of

oversize gaskets. During the first charge cycle it was noted that a minor pressure differential built up then decreased to zero. This indicated that the cell stack was leaking. In addition, upon attempting to discharge the cell, very poor performance was obtained.

The cell tanks were vented, disassembled, and the stack leak checked. It was readily apparent that at the higher state of charge, i.e., when less water was in the asbestos, the cell would leak across the stack. By further compressing the stack to 75 inch pounds bolt torque, i.e., increasing the asbestos compression, the leak was stopped.

Although the leak was stopped, subsequent performance did not improve upon reassembly. Preliminary discharge tests indicated that a cell reversal had occurred. Upon disassembly, two cells were found to have reversed.

Voltage probes of the cell stack after disassembly revealed the reversed cells were located on the extremities of the stack, i.e., cells number 1 and 6. Further inspection revealed that the hydrogen electrode of the H_2 end plate had been inadvertently inserted with its smooth surface adjacent to the electrolyte matrix, whereas the smooth surface had previously been placed adjacent to the separator on all previous runs. (Although the porous nickel electrodes are supposedly homogenous throughout, one surface appears slightly smoother than the other.) A series of tests was then conducted on the H_2 end plate electrode to determine the mode of failure. It was again determined that the electrolyte and gas ports were not the cause of the cell reversal. Brief runs using the end plates as a single cell showed that concentration polarization severely limited the current that could be obtained. By repeated washing of the end plate electrodes in acetone and boiling distilled water along with correcting the reversed electrode position, some improvement in performance was noted. However, this performance level was still less

than that required. Reversal of the H_2 end plate cell was therefore partially attributed to reverse placement of H_2 electrode. Inspection and test of the other reversed cell electrodes gave no indication as to the possible cause of reversal.

3.2.3.15 Run No. 13

Before continuing with cycle tests, it was deemed advisable to install another set of electrodes in the reversed cells. The 6 cell unit was subsequently reassembled with these electrodes replaced and readied for test. For this run, it was decided to check the performance at a 60 watt level for an eight hour period. If performance was found to be satisfactory, another attempt was to be made to complete the 48 hour continuous cycle test at the 75 watt level. In order to minimize the possibility of cell reversal, it was deemed advisable to heat the unit to the nominal $70^{\circ}C$ operating temperature before starting cycle tests. A small electric heater was therefore placed adjacent to the cell. Cycle testing was initiated when the internal temperature was near $60^{\circ}C$.

The results of this test are given in Figure 15. Performance appeared to be satisfactory during the first few cycles, i.e., 12 amp. discharge at 5 volts. At the start of the fourth discharge period with internal pressure near 300 psig, and temperature near $70^{\circ}C$ another ignition occurred. This ignition was much more severe than any of the others in that the gases escaped externally and the magnesium O_2 end plate ignited. The door of the test chamber was also blown open during the process (See Fig. 17). The subsequent magnesium fire was extinguished with the aid of chemical fire extinguishers. Disassembly and inspection of the unit revealed severe damage to the end plates and tanks (See Figs. 18, 19, and 20).

Review of all assembly and operating records for this run as well as a thorough inspection of the unit revealed the most probable mode of failure. A short section of mylon tubing was employed on the H_2 leg of the differential pressure transducer instead of copper or steel due to the necessity of insulating the two cell

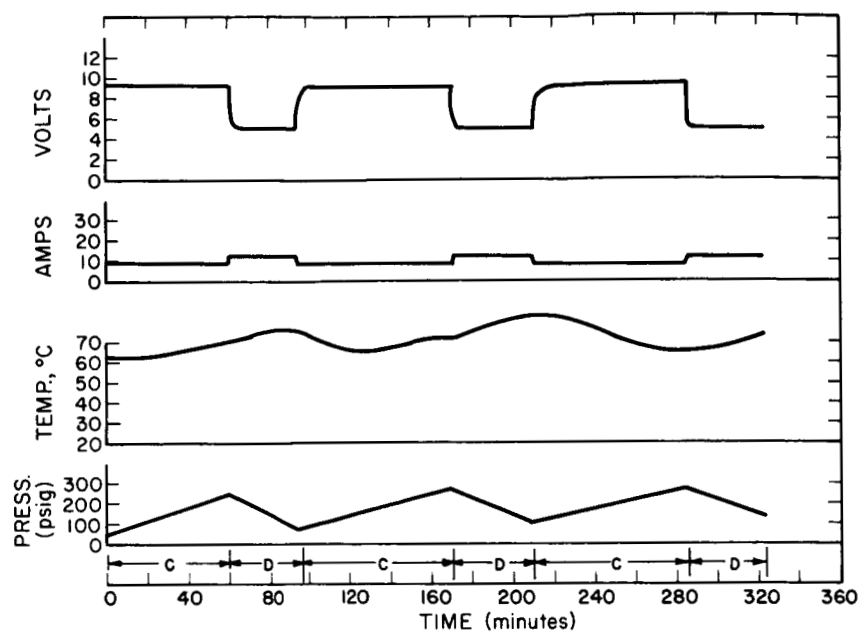


FIG. 15
PERFORMANCE OF UNIT
IN RUN NO. 13

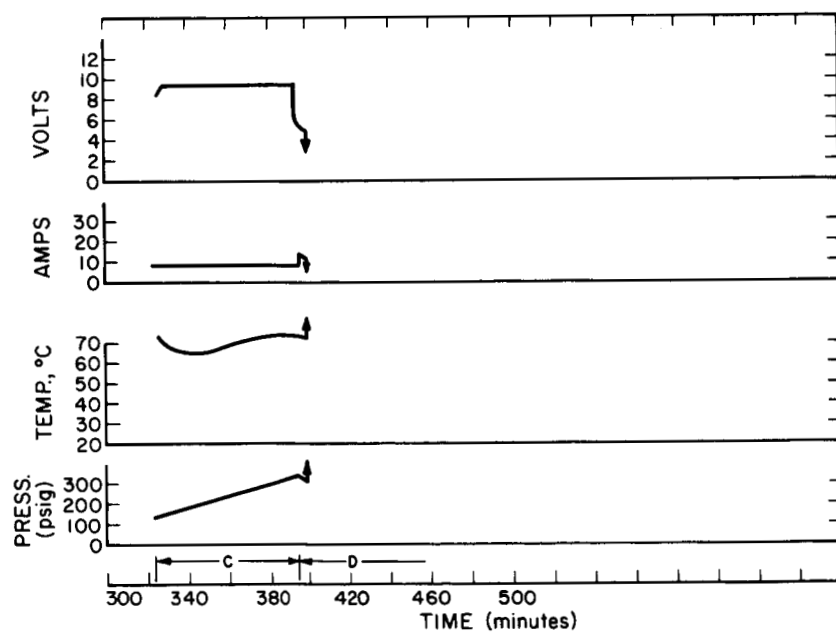


FIG. 16
PERFORMANCE OF UNIT
IN RUN NO. 13

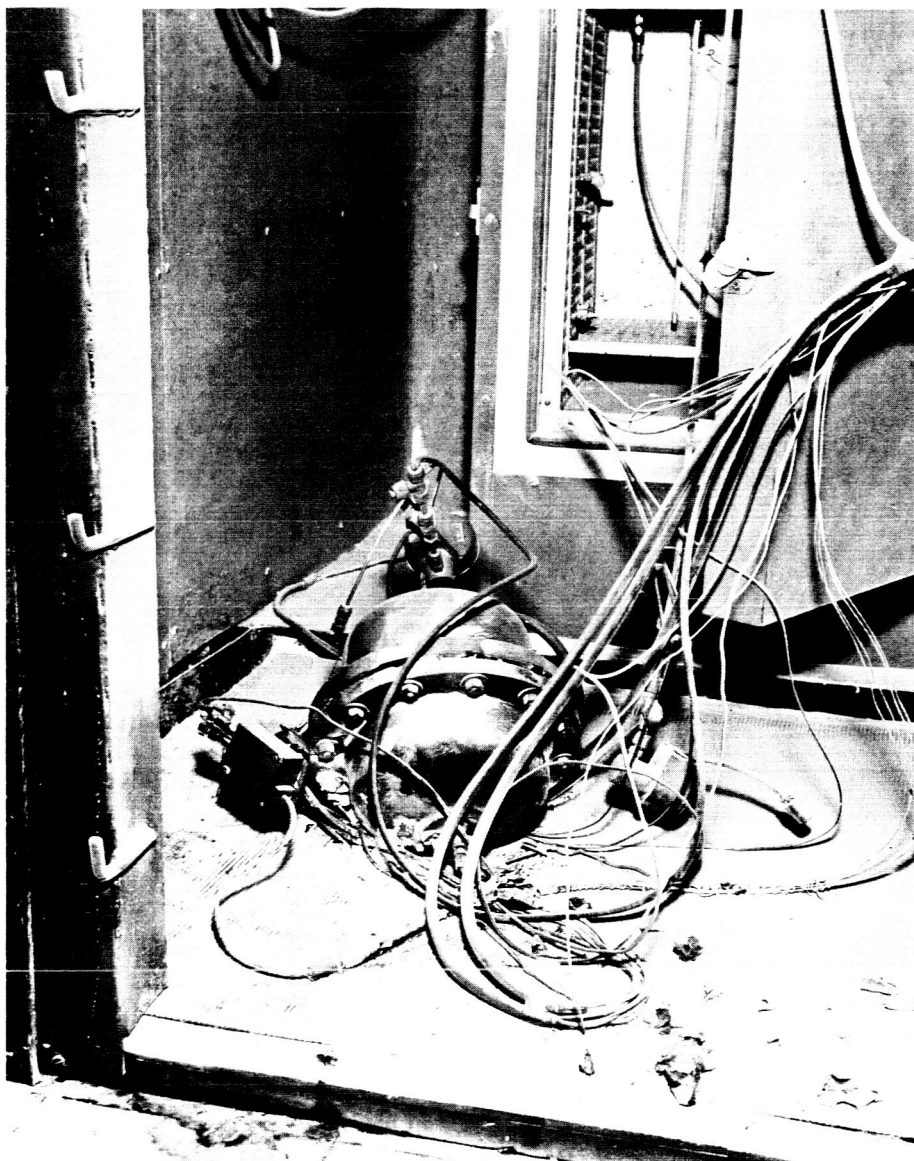


FIG. 17 FUEL CELL IN TEST CHAMBER AFTER EXPLOSION

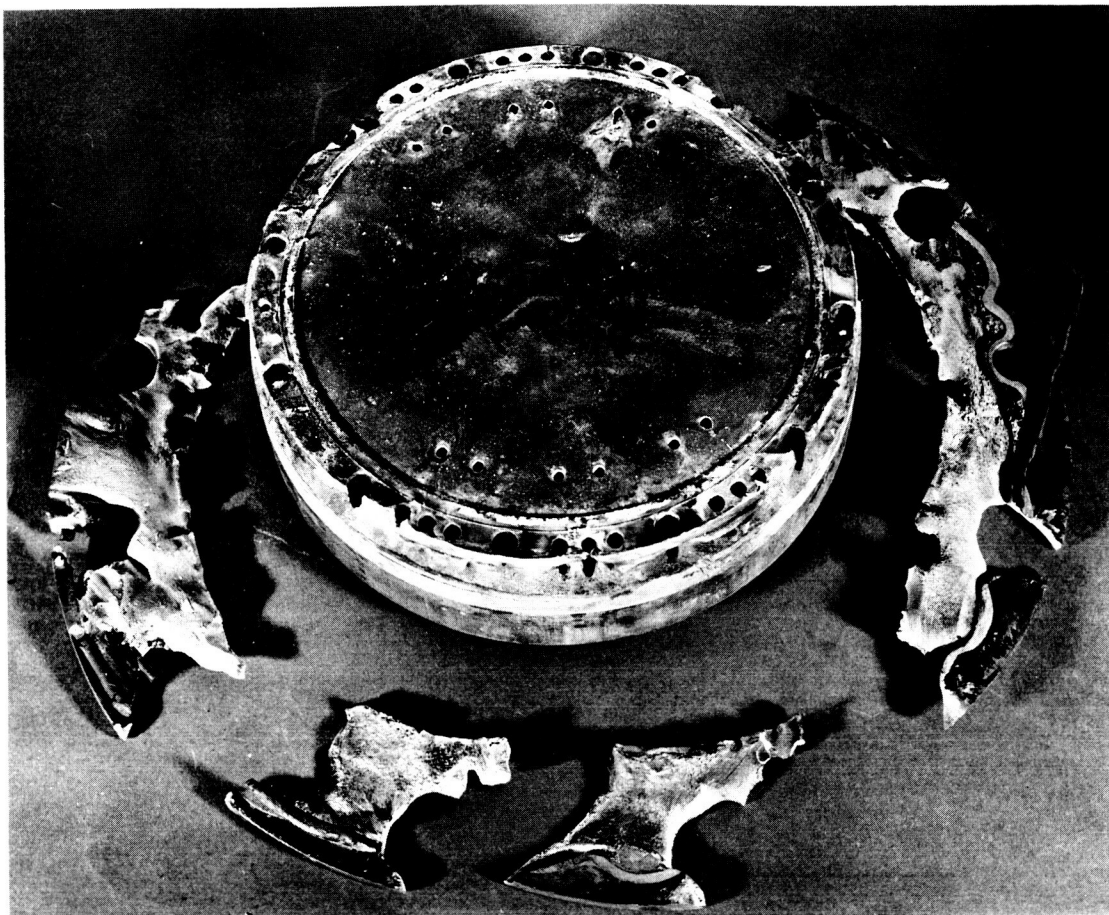


FIG. 18 OXYGEN END PLATE AFTER EXPLOSION



FIG. 19 GAS TANKS AFTER EXPLOSION

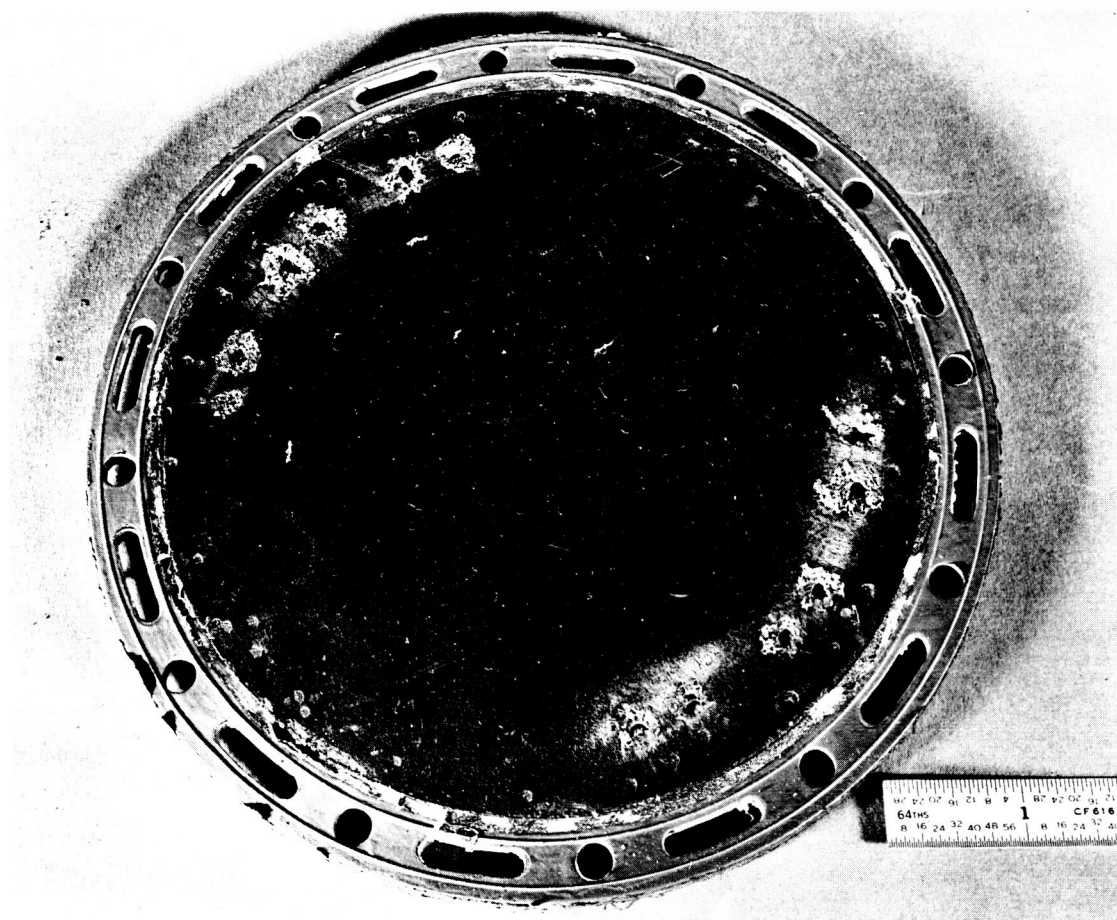


FIG. 20 ELECTRODE SEPARATOR ASSEMBLY AFTER EXPLOSION

halves. Although this nylon tubing has a considerably higher burst strength than the operating cell pressure, it is believed to have failed due to overheating by the external heater. The failure of this tubing would have suddenly released hydrogen, causing an excessive internal oxygen differential, and subsequent mixing and ignition.

3.3 Permeability Studies

The asbestos matrix is a very critical component of the fuel cell assembly. Its function is twofold (a) to serve as a water storage reservoir and (b) to prevent mixing of the hydrogen and oxygen gases through the cell stack. In the early stages of the test program (see Sec. 3.2.3.6) it was found that the type of asbestos which had been employed did not effectively separate the two gases. A simple leak test revealed bulk gas flow through the material (impregnated with the appropriate amount of electrolyte) upon application of only a fraction of a psi gas pressure. This permeable grade of asbestos was undoubtedly associated with some of the internal ignition problems in the first few runs. Replacement of this asbestos with two layers of another grade revealed much greater resistance to gas flow.

The above results pointed to the need for maintaining very rigid control over the type of asbestos to be employed within the cell. In order to carry out this control it was necessary to devise a test procedure for measuring resistance of the asbestos to gas flow. Such a test was devised and employed to measure the permeability of various grades and thickness of asbestos stock.

3.3.1 Procedure

Test conditions simulated those which are employed in actual fuel cell operation. A disc (or discs) of the asbestos materials was first cut to a diameter of 6 1/4 inches, and then impregnated with 25 percent potassium hydroxide solution. The amount of solution was held constant at 0.6 gms per gram of dry asbestos in the initial set of runs, but was later varied in order to test the effect of this parameter. After impregnation, the disc was allowed to

equilibrate in a polyethylene bag for at least 1/2 hour in order to insure uniform distribution of the electrolyte throughout the disc. Next, the asbestos disc was installed in a simulated single cell which consisted of two circular steel plates with the appropriate gas ports and electrode areas. Compression of the asbestos was carried out by tightening eight equally spaced bolts which passed through the periphery of the steel plates. The amount of compression was held constant in most of the runs at such a level that the final thickness was 4/7 of the initial asbestos thickness. For example, if two layers of .035" asbestos were to be employed, the final thickness would be 4/7 X .070" or .040", and the compression would be .030". Metal spacers of the appropriate thickness were placed between the plates in order to obtain the desired compression.

Hydrogen gas was applied to one side of the cell, and the exit tube from the other side was placed under a column of water in an inverted graduate. Gas pressures were increased in increments of 1 or 2 psi, and the system allowed to stand for approximately 10 minutes at each setting. The pressure at which initial flow was observed was noted (the "break through" pressure) and the flow rate at various pressures beyond this point were measured via displacement of water with time. Five types of asbestos were evaluated in this test series as follows:

- | | | |
|----|-------------------------|--------------|
| 1. | Johns Manville Asbestos | 0.020" thick |
| 2. | " " " | 0.035" thick |
| 3. | " " " | 0.060" thick |
| 4. | " " " | 0.060" thick |
| 5. | Unknown supplier | 0.060" thick |

There is no further data on any of the above materials except for nominal chemical compositions as follows:

Binder	< 3 %
Ignition Loss	<18 %
Asbestos	>95 %

3.3.2 Results and Discussion

Results of the permeability studies are given in Figures 21 through 25 . As would be suspected, the gas flow rate is appreciably reduced as the number of layers of asbestos is increased. For example, in Figure 21 , it is noted that with the 0.020" asbestos at 10 psi, the flow rate is decreased from 52 c.c./hr. to 2 c.c./hr. (extrapolated value), as the number of layers is increased from 2 to 4 respectively. Therefore, in doubling the number of layers, one obtains a 26 fold decrease in flow rate.

It should be pointed out that there is a significant difference in the permeability characteristics of each of the types of asbestos. No conclusion can be drawn at this time as to the cause of these differences. However, pinholes, binder content, and precompression due to mill processes are believed to be variables.

Permeability is also a strong function of electrolyte content. Inspection of Figure 25 reveals a sharp increase in gas flow as the electrolyte content is decreased from 0.5 to 0.4 gms of 25 percent KOH per gram of dry asbestos.

Experimentally, at a 0.4 ratio, hydrogen permeates rapidly at low pressure levels, then apparently the asbestos pores begin to plug up, increasing the flow impedance. Data points are therefore quite erratic, although after plugging, the same type of curve as that for the 0.5 and 0.7 ratio curves is apparent. (Not shown, in order to simplify the graph are the 0.6 ratio data. These lie midway between the 0.5 and 0.7 ratio curves). The significance of the apparent change in slope of the curves near the 200 cc/min. leak rate has not been determined.

These results are very significant in that they place a limit on the electrochemical capacity of the fuel cell for a given grade and thickness of asbestos. This latter conclusion is based on the fact that the amp-hr. capacity is directly proportional to the water content (3 a-h/gm) which in turn is proportional to the electrolyte content.

An additional parameter currently under investigation is that of the amount of compression. These results will be presented in the next quarterly report. In conclusion, it may be stated that these results have proved very useful in interpreting past performance of the cell, and will be of significant value in carrying out future tests.

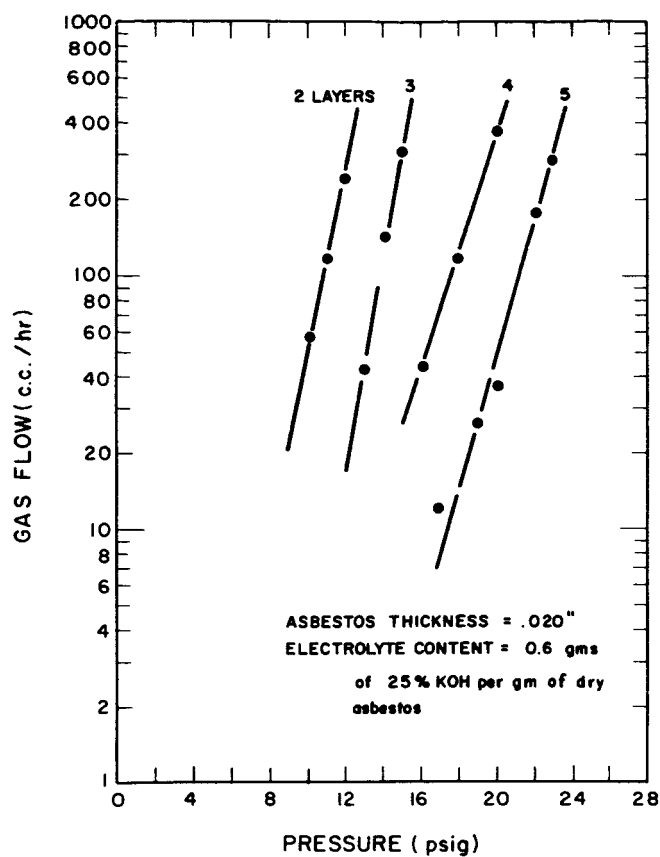


FIG. 21
PERMEABILITY OF .020"
THICK ASBESTOS

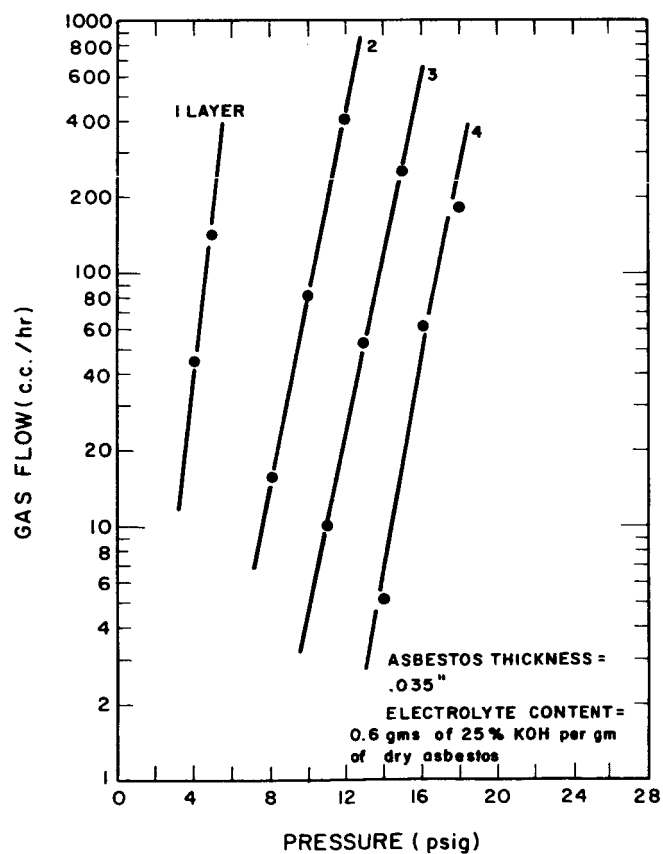


FIG. 22
PERMEABILITY OF .035"
THICK ASBESTOS

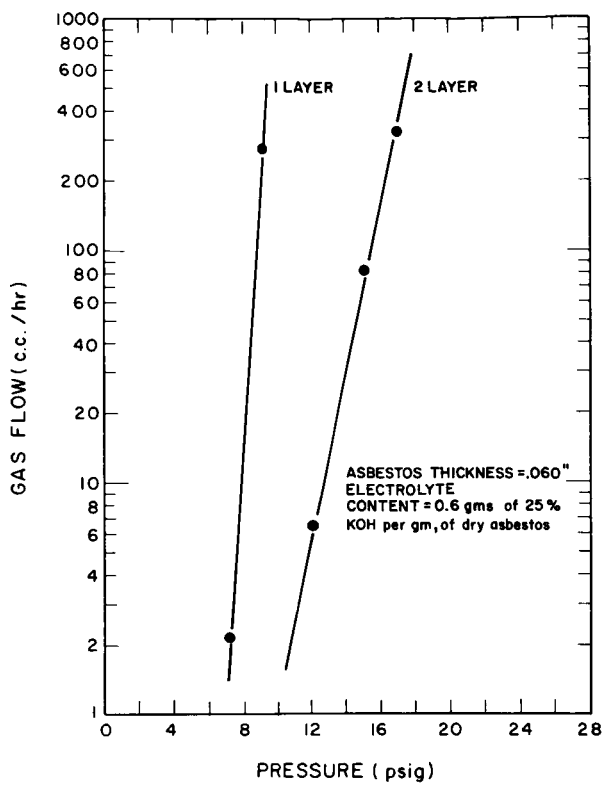


FIG. 23
PERMEABILITY OF .060"
THICK ASBESTOS

FIG. 24
PERMEABILITY OF ORIGINAL AND
ELECTROLYTIC GRADE ASBESTOS

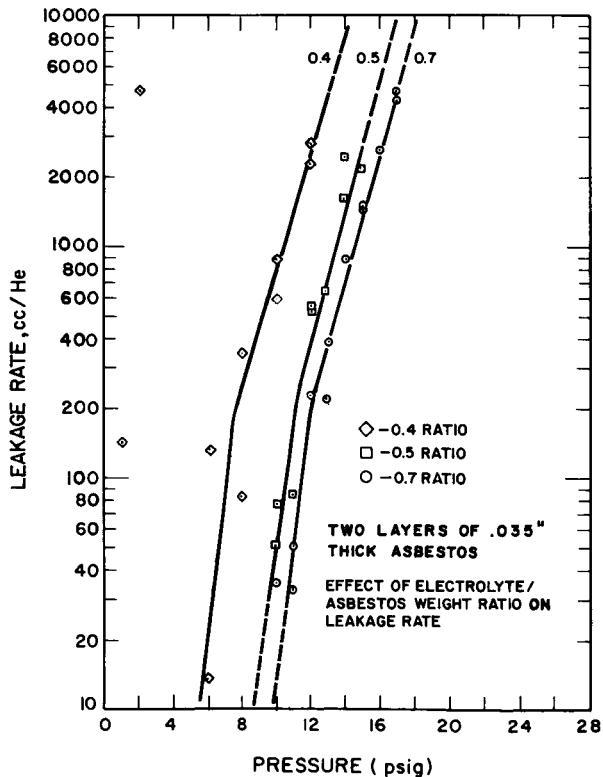
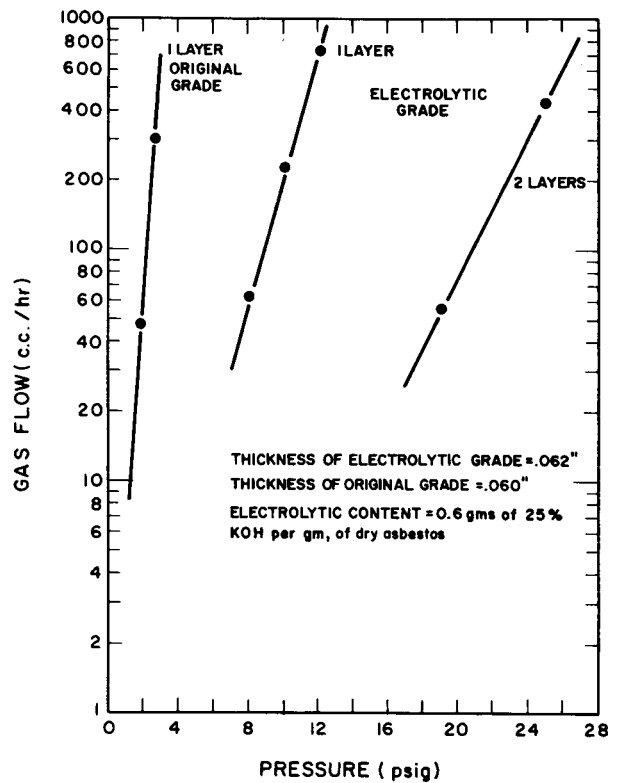


FIG. 25
EFFECT OF ELECTROLYTE CONTENT
ON PERMEABILITY OF .035" THICK
ASBESTOS

4. ANALYSIS OF RESULTS

The test program to date has yielded significant results. Modes of failure not previously exhibited with this type of cell, have repeatedly been demonstrated. A great deal of information and a much better understanding of the operating parameters has been obtained. Six critical factors not previously understood have been defined, and design criteria established. These being:

- a. Asbestos type requirements.
- b. Asbestos compression requirements.
- c. Electrolyte requirements.
- d. Gas port requirements.
- e. Separator seal requirements.
- f. Operational procedures.

Each of these factors are discussed in the following sections.

4.1 Asbestos Type Requirements

As a result of the thermochemical failures and poor performance exhibited by the 0.070" and 0.020" asbestos materials, it is readily apparent that an asbestos material must be carefully chosen. Highly porous materials (such as the 0.070") lead to mixing and subsequent reaction. Low porosity materials cause concentration polarization and result in poor performance.

Results to date indicate that a multilayer asbestos of medium porosity, i.e., similar to the 0.035" material will provide adequate performance, storage capability and effectively prevent gas mixing. (The term effective, as used here, is defined as the prevention of bulk mixing. Gas diffusion, however, will occur. Such diffusion mixing will only result in minor chemical recombination and formation of water at the electrode.)

Two candidate materials appear useful at this time. These are the 0.035" commercial and 0.060" electrolytic grades of asbestos. It is anticipated that other thicknesses of the electrolytic grade material will also be suitable. These other thicknesses will be evaluated in the near future.

Prior to the present program, various materials such as polypropylene, pure asbestos, and various felt materials were evaluated. All of these were eliminated due to poor chemical stability, lack of wet strength or poor electrolyte retention characteristics. Although other absorbent porous products might be suitable, future work will be limited to asbestos.

4.2 Asbestos Compression Requirements

In order to prevent leakage through any of the electrolyte retention materials tested to date, a certain compression of the material is required. As a result of previous tests, a 7/4 compression ratio appeared to be a satisfactory value. Above this ratio, electrolyte is squeezed out of the separator material and into the electrode area. This tends to flood the electrode. Below this ratio, gas leakage occurs, as was evidenced by Run No. 12.

Further testing of this factor, in order to determine allowable tolerance on the 7/4 ratio, is presently underway.

4.3 Electrolyte Requirements

Optimum conductivity of aqueous solutions of KOH occur at roughly 30 weight percent KOH. It is therefore readily apparent that this value represents a desirable concentration. Since the regenerative mode of operation used in the EOS design requires the removal and addition of water from the electrolyte as a function of charge and discharge, a 30 percent concentration cannot be held constant. However, the variation in concentration can be such as to minimize the change in conductivity. By maintaining an initial concentration of $\approx 25\%$ KOH, the concentration at full state of charge becomes $\approx 35\%$. Therefore, only minor changes in cell impedance occur as a function of state of charge.

The quantity of electrolyte is the other important requirement. If insufficient electrolyte is initially charged into the asbestos matrix, gas leakage will occur. Conversely, too much electrolyte will cause electrode flooding. Tests conducted to date, using 0.035" commercial asbestos, indicate that a 0.7/1 initial weight ratio of electrolyte to asbestos is optimum. At full state of charge (for a 750 n.m. orbit) this results in an $\approx 0.5/1$ ratio, which is quite satisfactory to prevent gas mixing. For higher orbits, i.e., those requiring longer discharge times and larger capacities, additional layers of asbestos will be required in order to maintain the 0.5/1 final ratio.

4.4 Gas Port Requirements

During the test program, there were indications that 100-150 ma/cm² represented a limiting current density. It is believed that this limit was imposed by insufficient gas port area, in effect starving the electrodes, resulting in extreme concentration polarization. A new gas port design is being prepared which will both increase the gas port area, and better distribute the flow of gas.

4.5 Separator Seal Requirements

Two failures could be directly attributed to gasket and seal problems. In addition, unsatisfactory tolerances on rubber gaskets contributed to two other failures. Therefore, a new type of seal, eliminating extrusion, cold flow and critical dimensional tolerances has been designed. This design incorporates a continuous rubber compression seal integral with the separator plates. Insulation and cell spacing will be accomplished using a rigid flat plate spacer with appropriate ports and bolt holes.

4.6 Operational Procedures

During initial testing of the cell, a variety of assembly and start up procedures were used. As experienced with the cell developed, it became apparent that a standardized procedure was required. Therefore, a detailed check off list was prepared listing the assembly and checkout steps. In addition to improving quality

control, the check off list contains provisions for recording data on dimensions and weights which might be critical.

Operational procedures during performance test are not as yet clear cut. Provisions have been made for automatic cycling, but it is evident that monitoring of the unit by technical personnel will be required until reliability is improved.

5. CONCLUSIONS

Results to date have been both good and bad. Reliability obviously requires considerable improvement. However, performance on both charge and discharge has been quite satisfactory when the cell is operating properly. Most important though is the fact that no fundamental problem has arisen that cannot be overcome by engineering improvements. Further, important advantages of the H_2/O_2 regenerative system still remain valid. These include (a) the state of charge of the battery can be easily determined by a simple pressure measurement (b) the battery can be thermally sterilized (c) higher energy to weight ratios as compared to conventional secondary batteries can be achieved and (d) they have potentially longer cycle life since no solid material solution and deposition steps are required as with conventional secondary batteries.

6. PLANS FOR THE NEXT QUARTER

Revision of the design parameters of the test model have been proposed and approved. Design parameters that will be modified include:

- a. Separator gasket.
- b. Elimination of stearic acid tankage.
- c. Increase size of gas ports.
- d. Increase cell stack bolt diameter.
- e. Use of metallic pressure balancing diaphragm.
- f. Eliminate plastic tubing.
- g. Eliminate magnesium in critical external structural portions of the cell.
- h. Improve flange "O" ring design.

Separator gasket design has been analyzed in great detail in light of the gasket quality control problems that have occurred during the program. Two factors have been noted as major problem areas; these being gasket thickness and gasket extrusion. These problems have been discussed with the Parker Seal Company, and an excellent solution determined. This solution involves the use of a Parker Seal called a "Gask-O-Seal." In essence, it is an "O" ring type seal contained on its inner and outer diameters by a metal or plastic plate. With this type seal, gasket extrusion is prevented, sealing is accomplished, separator spacing and thus gasket compression will be more uniform and quality control more assured.

Stearic acid and its tankage caused a number of problems during the test program, and has been suspected of contamination of the electrodes resulting in cell reversal. Since the thermal storage section of the follow-on program has been dropped, all features of this phase can be eliminated, greatly improving the reliability of the system.

Modification of the gas port design is desirable for two reasons: first, due to gas distribution, and second, due to potential gas leaks. The present design utilizes drilled holes from the gas manifold to the gas distribution screen. Due to weight constraints, causing separator thickness constraints, the diameter of these holes are not considered adequate for good gas flow. In addition, the drill holes, which extend to the outer periphery of the separator plate are subject to leakage. This leakage is strongly believed to be a major contributing cause of the thermo-chemical reactions occurring during the initial testing.

Increasing the cell stack bolt diameter is desirable from two standpoints; it allows us to use stainless steel bolts in place of the less corrosion resistant 4130 bolts presently used, and it will result in a larger gasket sealing area. A 1/4-28 bolt in place of the present 10-28 bolts will be satisfactory.

An improved pressure balancing diaphragm is a prime necessity. It has been readily apparent that volume unbalance and thus pressure unbalance can easily occur as the variables of the cell stack are changed. The present rubber diaphragm volume is inadequate to cover the volume imbalances encountered. In addition, during the development testing, a rubber diaphragm may be subjected to conditions beyond its stress limits, resulting in failure and a thermochemical reaction. A flexible stainless steel bellows will remedy most of this problem. Such a bellows can be fabricated, and is commercially available. Its characteristics are such that a significant volume change can be obtained with a relatively small pressure differential. Further, a design incorporating two diaphragms would be even more suitable.

Elimination of all plastic pressure tubing from the test environment will eliminate a repetition of the type of failure which damaged the 75 watt test model.

The failure mode of the 75 watt model indicated a serious design deficiency. By using a magnesium plate extending between the tank flanges as the cell stack gas seal and positioner, the cell container

pressure integrity was compromised. Further, the plate weld is subject to leakage as occurred during one test. This feature can quite readily be eliminated by improved design.

The "O" ring design used on the tank flanges of the 75 watt unit was inadequate. This can be readily remedied by either using a Gask-O-Seal type design, or an improved recessed "O" ring gland design.

In addition to improvements in a redesign of a nominal 75 watt unit, a 6 inch electrode diameter single cell unit will be fabricated. This cell will be used for a number of purposes, including:

- a. Single cell test in a secondary mode for a 48 hour period at 10-15 watt level.
- b. Screen multi-cell electrodes prior to use to prevent cell reversal problems.
- c. Asbestos matrix evaluation

The cell design will include internal tankage and will be suitably instrumented.

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